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COUPLED GRANULAR/CONTINUOUS MEDIA FOR PERPENDICULAR MAGNETIC RECORDING*

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While the most promising longitudinal recording systems cannot surpass the theoretical limit of about 200 Gb/in^2 for areal recording density and the demand for higher densities is permanently increasing, the perpendicular magnetic recording constitutes the realistic issue to the longitudinal one. The perpendicular magnetic recording offers significant advantages, the most important being stronger write and read fields, and therefore the use of media of higher anisotropy, smaller grain size, higher signal-to-noise ratio, and a better thermal stability. Unfortunately, the perpendicular recording has to cope some important physical and technological difficulties. To overcome them, many ingenious solutions were proposed. In this paper the coupled granular/continuous (CGC) media, a subtle association of the continuous and, respectively, granular media, are analysed from the viewpoint of their magnetic and recording properties. The challenges and possible improvements of CGC media are discussed.

Key words: Perpendicular magnetic recording; Coupled granular/continuous media; Areal recording density; Signal-to-noise ratio; Thermal stability.

1. INTRODUCTION

The perpendicular magnetic recording utilising pole heads and perpendicular media with soft underlayer represents the immediate alternative to the longitudinal recording [1]. At a tolerance of 20 dB of the signal-to-noise ratio (SNR), and for a perfectly homogeneous medium, the limit set on the basis of thermal stability considerations for the perpendicular recording is at least 500 Gb/in^2 [2]. In fact, this last limit can be overcome. Today, we talk about an areal recording density that can reach about 1 Tb/in^2, corresponding to a bit size limited to low 20 nm [3].

On the other hand, the SNR is proportional to the number of magnetically decoupled ferromagnetic particles or grains in a recording bit and, therefore, the particle size should be in the range of few nanometers. However, such small particles become thermally unstable as their size is close to their super-paramagnetic limit that is when the thermal fluctuations can determine the magnetization reversal against the magnetic anisotropy energy of the particle. This effect is described by the thermal stability factor

$$\kappa = \frac{K_u V}{k_B T}, \qquad (1)$$

where K_u is the uniaxial magnetocrystalline anisotropy constant, V is the grain volume, k_B is the Boltzmann' constant, and T is the temperature. For a good thermal stability of the grain, κ must be at least 60 [4].

Equation (1) synthesizes the famous *tri-lemma* of magnetic recording (thermal stability, media noise, and writability): To obtain high areal recording density, without sacrifying SNR of the media, we must reduce the volume V of grains. But, in order to preserve or increase the thermal stability of the recorded bits, one should increase the media anisotropy K_u as much as the magnetic field of the write head permits, because high K_u granular media have very high saturation fields, leading to huge writability difficulties. Indeed, to record these media one needs very high fields, which are impossible to obtain due to the limited saturation magnetization of the head materials in use today. A material with an uniaxial magnetocrystalline anisotropy K_u of one order of magnitude higher than that of currently used Co-based alloys should be employed to achieve ultrahigh density recording medium.

* Invited paper

They are such materials. So, the $L1_0$ phase of FePt alloy is one of the most promising, due to its very high value of K_u ($\cong$ 7 MJ/m^3), which leads to thermally stable grains with sizes down to 3-4 nm. Unfortunately, FePt films deposited at room temperature are magnetically soft, due to their metastable disordered A1 structure. Therefore, a high-temperature process, such as deposition on a heated substrate or postannealing above 600°C must be used to obtain the fully ordered $L1_0$ structure of the films. To reduce the ordering temperature of these processes, several methods have been recently developed.

The writability problem can be also solved using various assisting methods, including: domain-wall-, heat-, microwave- and precessional-assisted reversal methods.

With extremely high recording density applications, the SNR of the medium varies opposite to the cube of the plane diameter of the grain. That is why an increase of the density demands a decrease of the grain size. From this point of view, perpendicular recording is preferred to longitudinal one, as it allows for thicker media to be used. It offers many meaningful advantages: **i**. the use of probe heads, able to generate stronger fields, which, in turn, allows for the use of media with higher anisotropy; **ii**. smaller grains; **iii**. a higher SNR for an imposed thermal stability.

There is also a fundamental problem to be dealt with the perpendicular media: the distribution of the material properties [5]. With conventional perpendicular recording, even a small distribution of the orientations (usually within a cone of 5°), and a small distribution of the anisotropy (≈ 0.1) greatly increases the transition parameter, even that this increase is partially compensated by the low value of the intergranular exchange interaction. Or, SNR varies opposite to the second power of the transition parameter. Since this parameter depends on the distributions, having a minimum limit value in accordance with the size of the grains, these effects will further limit the recording densities that can be achieved in conventional perpendicular recording.

Most of these problems can be overcome by adopting new media structures.

An important reason that impedes a complete valorisation of the potential of perpendicular recording is just the granular nature of the media and thus the noise due to the irregularities of bit transitions. This noise is due to the intergranular exchange coupling, to the distribution of the anisotropy field and to the write field gradient. It can be reduced with the help of dense and uniform pinning sites.

The intergranular exchange coupling is usually reduced as much as possible, even if an appropriate amount of this coupling is convenient to improve the thermal stability (it leads to the extension of the superparamagnetic limit of magnetic recording) and the writability (it reduces the saturation field). But if this coupling is controlled by grain segregation, the increased thermal stability leads to a reduction of SNR. Thus an optimal value of the intergranular exchange coupling must be found, following from the tradeoff between SNR and thermal stability.

The solution is offered by the *coupled granular/continuous* (CGC) *media* [6,7].

A CGC medium is made up of a continuous layer C with a strong exchange coupling, exchange coupled with a perpendicular granular layer G. The small grains of the G layer provide dense pinning centres for the walls in the C layer. The recorded transition consists of a usual structure in the G layer and of a domain wall in the C layer. The transitions in the two layers overlap so that the C domain wall is pinned by the transition in the G layer and the transition of the CGC medium is given by the frontiers of the grains. Moreover, the tendency to minimize the wall energy leads to some smoothening processes of the walls, the result being a supplementary reduction of media noise.

Both thermal stability and SNR can be improved by adjusting the structure and the parameters of the CGC media, because the exchange-coupled continuous layer, that achieve an *indirect* coupling of the grains of the G layer, ensures a high thermal stability, while the granular host layer contributes to the reduction of the media noise and to improvement of the SNR of the written bits and of writability.

2. PRINCIPLE AND STRUCTURE OF COUPLED GRANULAR/CONTINUOUS MEDIA

Perpendicular coupled continuous/granular (CGC) media are made of a continuous layer C, of thickness *c*, without pinning centres, exchange coupled with a perpendicular granular layer G, whose thickness is *g* (Fig.1), both films being placed onto a soft magnetic underlayer (SUL). This structure combines the useful properties of perpendicular continuous and granular media: the small grains of the G layer, which are stable as a result of their coupling with the C layer, provide dense pinning centres for the walls in the C layer. Since the grains cannot reverse their magnetization at the centre of the bit without nucleating a domain in the C layer, the thermal stability of the CGC medium is better than that of a decoupled granular medium [8].

The recorded magnetic transition has a dual structure, which consists of a usual structure in the G layer and of a domain wall in the C layer. The two transitions overlap so that the transition in the continuous C layer is pinned by means of the one in the granular G layer: the domain wall in the C layer can be moved only if reversing the magnetization of the grains in the G layer. Thus, the size of the unity switching at the transition (the activation volume) is given by the size of the grains in the G layer, and the shape of the transitions at the surface of the CGC medium is given by the limits of the same grains. Under certain circumstances, the tendency to minimize the energy of the walls leads to a reduction of the irregularities of bit transitions in the case of CGC media. The wall in the C layer moves away from the limits of the grains, so that the transition noise is reduced too [10]. This proves that the direct relationship between thermal stability and noise can be broken in a controlled way, thus evading the conventional limits of the recording density.

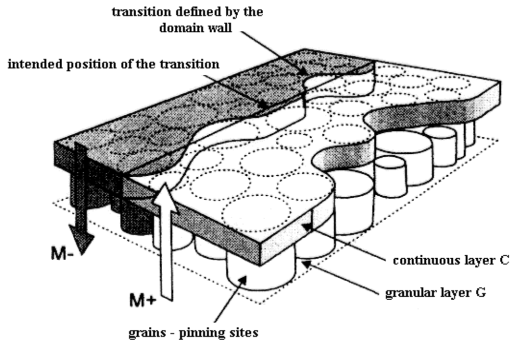

Fig.1 – The principle representation of a CGC medium. The location of the domain wall (of the transition) in the C layer is imposed by the orientation of the grains magnetization in the G layer [9].

In fact, the C layer connects indirectly the magnetic grains in the G layer, through the interlayer exchange coupling, which is called a *distribution narrowing effect* [11] due to the fact that it leads to the reduction of the magnetic anisotropy. In turn, this effect contributes to the improvement of the overwrite characteristics.

The CGC media use Co-Pt(Pd) multilayers [6,12,13] or amorphous CoCrTb [14] or Pt-rich CoCrPt alloy films [15] or even CoCrPtB (these last ones are also called capped media or stacked media) for the continuous layer and CoCrX (usually CoCrPt) alloy films with weak lateral exchange coupling for the granular layer – but, in principle, the CGC concept may be extended to any continuous films pinned by an underlying granular film. The CoCrPt-SiO_2 alloy with magnetically decoupled small grains of less than 5 nm average grain size was also proposed for the granular layer [11,16,17], because the magnetic grains are better isolated by oxide material segregated into the grain boundaries. Usually, the CGC structure is deposited onto a Ru magnetically soft underlayer.

It is interesting to note that the concept of CGC media was derived from that of the exchange coupled composite media. On the other hand, the CGC media structure is a path leading to percolated perpendicular media [18].

In order to further decrease the transition noise, it was also proposed to combine the idea of exchange spring media with CGC media: an extremely hard magnetic continuous top layer is exchange-coupled to a granular bottom layer [19]. Even if the granular G layer has not intergranular exchange coupling and the hard magnetic continuous layer can not be recorded directly because of its very large anisotropy, due to the coupling to the softer granular G layer a domain wall formed in the G layer can propagate in the hard C layer if the writing field is larger than the pinning field. Indeed, in this case the hard C layer has a very small domain wall width ($\propto 1/\sqrt{K_C}$), which potentially leads to the reduction of the transition width and, therefore, of the jitter.

An alternative to the CGC structure of media is the *cluster-pinned recording media*, consisting of a nearly defect-free continuous thin film with high perpendicular anisotropy, exchange coupled to an adjacent layer of nanoscale high-anisotropy clusters [20]. The small number of defects leads to easy nucleation and domain-wall motion in the C layer, thus to a low coercivity, which can be well controlled by variations in the size, density and coupling of the clusters, as well as film thickness. The clusters act as pinning centers and control – also *via* the thickness c and anisotropy K_C of the C layer – coercivity, jitter, and other properties of the medium. This time the pinning of C domain-walls by the clusters in the G layer is strong, and the domain wall remains narrow (and, therefore, able to support high storage densities) due to the presence of the highly anisotropic continuous layer, while the structure is quite robust form the viewpoint of the thermal activation.

3. MAGNETIC AND RECORDING PROPERTIES OF CGC MEDIA

Since the two films are exchange coupled, the domain wall in the C layer moves away from the grains limits only if the magnetization of the grains moves away from the direction of their easy axes. It is assumed that the wall is of a Bloch-type, and that the remagnetization of the grains takes place by coherent rotation [9]. The last hypothesis, even if extremely simplistic, represents a satisfactory first approximation for the length scale of the process.

The energy of the wall in the C layer, whose areal density is

$$\sigma_p = \sqrt{A_C K_{u,C}}\ , \tag{2}$$

where A_C and $K_{u,C}$ represent the exchange and the uniaxial anisotropy constants of the material in the C layer, is directly related to its area. At a given thickness c, it is proportional to the length of the wall, so that a plane wall is energetically preferable. The energy of the transition is minimum when the reduction of the wall energy is compensated by an increase in the anisotropy energy, which is for every grain

$$W_g = K_{u,G} V \cos^2 \theta\ , \tag{3}$$

where $K_{u,G}$ represents the anisotropy constant of the G layer, and θ is the angle between the grain magnetization and its easy axis. The reduction of the bit transition irregularities is done by means of a mechanism controlled by the process of minimizing the energy of the domain walls. The degree to which the irregularities are reduced depends on the ratio between the wall energy and the energy barriers existing in the G layer, so that at a given total thickness of the medium, the effect can be controlled by simply varying the ratio $\rho = c/g$ between the thicknesses of the two composing layers. At a given wall energy, the transition irregularities can also be reduced by reducing the exchange energy between the two layers [9].

Three mechanisms of smoothing the wall shape in the C layer have been identified [7,10]. They differ according to the way of altering the magnetic state of magnetization in the G layer. Considering the same total thickness of the CGC medium, but a different ratio $\rho = c/g$ between the thicknesses of the two composing layers, these mechanisms are:

(i) *Stable reversible smoothing*, corresponding to a low value of the ρ ratio. The force acting on the domain wall causes the inclination of magnetization and this inclination is transmitted to the grains of the G layer. However, the wall energy is low, so that the corresponding force only produces a reversible change of magnetization. This smoothing reduces the irregularities observed at the surface of the C layer more than in the G layer, where the transition closely follows the irregularities of the well-segregated grains.

(ii) *Stable irreversible smoothing*, which corresponds to the optimal value of the ρ ratio: The stronger force acting on the domain walls lets the head field surpass the energy barriers associated to the grains that would otherwise contribute to increasing the irregularities or the apparent size of the cluster. This is similar to an increase in the head field gradient, allowing for the conversion of big clusters into smaller ones. When the head field is removed, the walls no longer move because the force acting on them is not enough in order to reverse the magnetization of the grains in the G layer.

(iii) *Unstable irreversible smoothing*, high values of the ρ ratio. The force onto the wall is further increased, supporting the action of the head field, as in the previous case. But now, when cancelling the head field, this force is strong enough in order to reverse the magnetization of the grains in the G layer. Subsequently, the walls are mobile enough and they can find positions of a relative energetic minimum, at a certain distance from the desired location of the transition, especially at the corners of the transition zone. This leads to curving the transition, and produces an additional noise.When the energy of the wall is very low, CGC media practically behave as exchange coupling granular media. When the wall energy is increased, there appear small clusters of magnetic grains, which leads to an increase in the experimentally observed SNR, even this increase is limited by the wall dynamics.

When the ρ ratio increases, one obtains a higher inclination of the hysteresis cycle at the coercivity point and a better rectangularity factor S^*, which leads to improved thermal stability and writing sensitivity. The nucleation field H_n of the CGC medium increases as compared to that of a simple granular medium, which also determines an increase in the S^* factor, while the distribution of the switching field is narrower [21].

Nevertheless, the significant improvement of SNR of CGC media, of over 1 dB as compared with that of a simple granular medium, cannot be explained simply by the transition smoothing effect described before. Some experimental results also suggest another complementary mechanisms [7, 17].

Thus, the increase of the thickness of a Co/Pd multilayer onto a granular CoCrPt-SiO_2 layer leads to the decrease of the coercive field H_c and of the saturation field H_s, while the nucleation field H_n increases, as well as the slope of the hysteresis loop at coercivity. These results prove that the exchange coupling in CGC becomes larger when the thickness of the continuous layer is thicker. However, the switching field distribution becomes narrower with thicker C layers, which leads to narrower distributions of coercive field H_c.

The thermal stability factor κ increases, for example from 60 to 100 when the thickness of continuous Co/Pd multilayer deposited onto a granular CoCrSiPt-SiO_2 increases from 0 to 6 nm – effect due to the increase of grain volume (K_u is constant), thus leading to the enhancement of the energy barrier. The optimum continuous layer thickness *c* depends on the C layer material.

Neither the increase of SNR can be completely explained by the increase of the slope of *M-H* loop at coercivity [21]. It is most presumably that it is due to the connection of decoupled magnetic grains in the G layer by means of the interlayer exchange coupling; this connection increases the switching (activation) volume involved in the magnetization reversal and, consequently, the thermal stability of CGC media. On the other hand, larger switching volumes can indicate a magnetization reversal by a noncoherent mode. Nevertheless, the angular dependence of coercivity of CGC media suggests rather that CGC media with continuous layer thickness of less than few nanometers reverse by coherent mode, similar to the simply granular media, presumably due to the very weak intergrain exchange coupling. That is why the SNR of CGC media kept high values despite the increased switching volume.

In order to explain the sheared shape of hysteresis loop of CGC media, one can also suppose that the top C layer exhibits also a granular structure, with a intergranular exchange coupling stronger than that in the G layer.

An important feature of CGC media is the tendency to expand the written tracks. Or, the maximum benefit of the CGC structure would be realized if the erase bands were to be removed. This remark leads to the analysis of possibility to apply the discrete track media concept to the CGC structures, because thus one can eliminate the probability to have some isolated grains in the written track that reverse accidentally their magnetization. As technique devoted to this aim, the use of guard-band media, obtained by ion irradiation, are more convenient than lithographic or ion implantation patterning [22, 23, 24]. These guard bands have reduced coercitivity and thus higher permeability, improving the write performance of CGC media.

The use of a cap CoCrPt layer as continuous layer inside a (Co/Pd) multilayer leads to some significant improvement. Then the grain boundaries are thicker than those of media with a multilayer, leading to reduced intergranular exchange coupling [22].

4. CONCLUSIONS

In this paper, a new type of perpendicular recording media is analysed from the viewpoint of their magnetic and recording performance.

The basic principle of the coupled granular/continuous (CGC) media, made up of a continuous layer C exchange coupled with a perpendicular granular layer G, is that the small grains of the G layer, whose intergranular exchange coupling can be well controlled *via* the exchange interlayer coupling, provide dense pinning centres for the walls in the C layer, thus improving the thermal stability and increasing the SNR of the written bits and writability. Both thermal stability and SNR can be improved by adjusting the structure and the parameters of the CGC media, particularly the material, structure and thickness of the C layer. On the contrary, it is difficult to reduce and control the exchange interactions in the G layer by means of segregation without sacrificing its anisotropy. This drawback can be overcome by using a granular monolayer of decoupled superparamagnetic nanoparticles [1], which would reduce the magnetic interactions that inhibit the self-ordering of the magnetic arrays.

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